Reading: Chapter 30, Sections 30.1-30.4
Online course evaluations
Exam 3: **Wednesday, December 18; 4:30-6:30** ; review and practice exam posted
Room: MacKay 0117
Essay: Thursday's lecture

Last time: **Other Planetary Systems**

- Imaging of planets – difficult, but not impossible
- Detection by orbital motion ("radial velocity)
- The *Kepler* Mission - planets are everywhere!
- > 4000 exoplanetary systems now known
- Properties of exoplanets - are they representative?

Today: **Life beyond Earth: The Drake Equation**

- Parameterizing our ignorance
  - breaking one big question into many small ones
- Astronomical, Biological, and Sociological factors

A Final Question: Are We Alone?


SEARCHING FOR INTERSTELLAR COMMUNICATIONS

By GIUSEPPE COCCONI* and PHILIP MORRISON†

Cornell University, Ithaca, New York

The Optimum Channel

846 NATURE September 19, 1959 Vol. 184

The reader may seek to consign these speculations wholly to the domain of science-fiction. We submit, rather, that the foregoing line of argument demonstrates that the presence of interstellar signals is entirely consistent with all we now know, and that if signals are present, the means of detecting them is now at hand. . . The probability of success is difficult to estimate; but if we never search, the chance of success is zero.

A Final Question: Are We Alone?

Towards an answer: The Drake Equation
(Frank Drake, 1962)

F.D. Drake, 1960

F.D. Drake, 2014

$$N = R_s \times f_p \times n_p \times f_L \times f_i \times f_c \times L$$

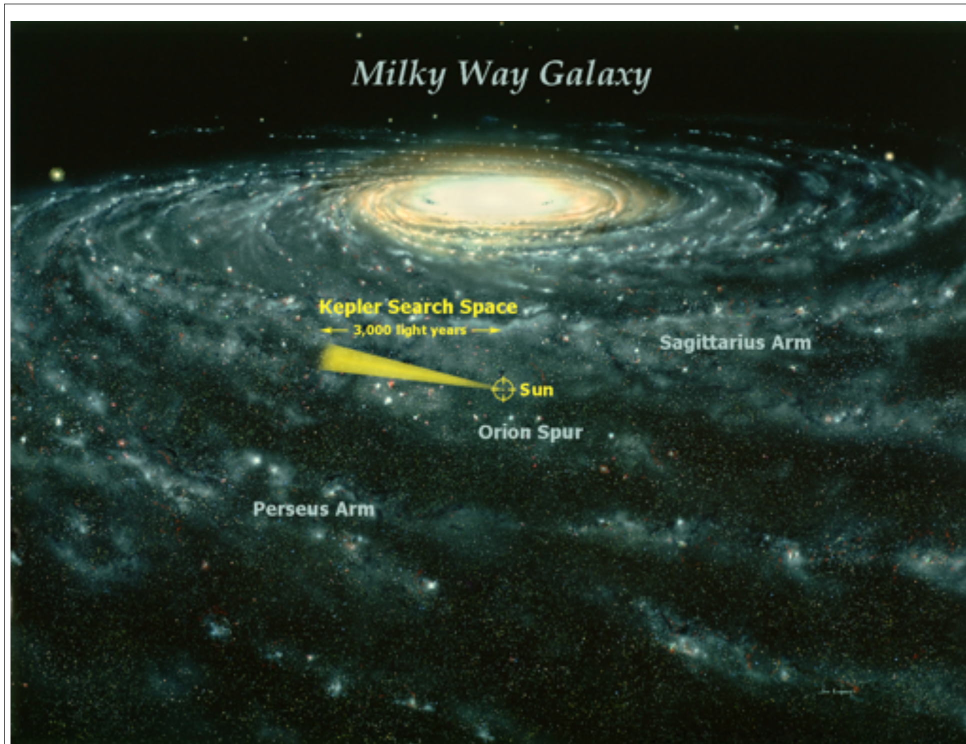
original form

The Drake Equation (1962)
parameterizing our ignorance

$$N = R_s \times f_p \times n_p \times f_L \times f_i \times f_c \times L$$

N is the number of communicating civilizations in the Galaxy today

Astronomical factors	= R_s **(annual rate of star formation)** x f_p **(fraction of stars with planets)** x n_p **(# of planets with conditions for life)**
Biological factors	x f_L **(fraction on which life develops)** x f_i **(fraction that develop intelligent life)**
Sociological factors	x f_c **(fraction that develop communication)** x L **(# of years communication continues)**



Astronomical Factors: Sun-like Stars

R_s – how many "useful" stars, out of 250,000,000,000 in our galaxy, form each year?

- long lasting - to allow complex life to develop
  - 3.5 - 4.0 billion years for the Earth
- quiet and steady energy production
  - few big flares or other 'stellar flares'
  - no binary companion
- about 1/3 of all stars are "useful"

R_s **~ 8 stars / year**

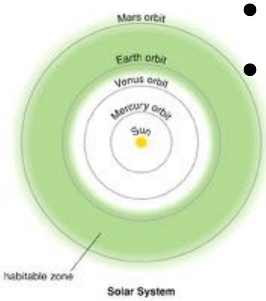
Astronomical Factors: Fraction of Stars with Planets

- star formation pictures - lots of protoplanetary disks
- searches for other planets...
- Planets are COMMON around single stars!
- future directions:
  - ground--based studies
  - space--based transit searches (2009-2020+)
  - space--based imaging/spectroscopy (2018 - ?)

f_p **~ 0.9**

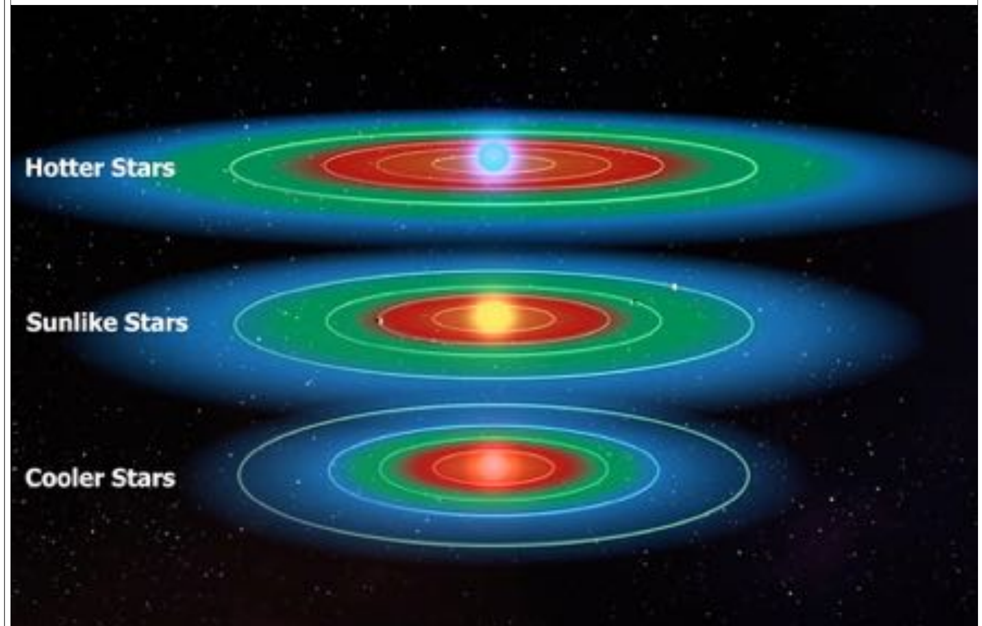
n_p = habitable planets: the ‘Habitable Zone’

- water essential to life (as we know it)
- liquid water has to exist on (or in) the planet
- must be right distance from star
  - heat from star ~ maintain $0^oC < T < 100^oC$
  - too close - runaway greenhouse (Venus)
  - too far - CO_2 ice - no greenhouse (Mars)



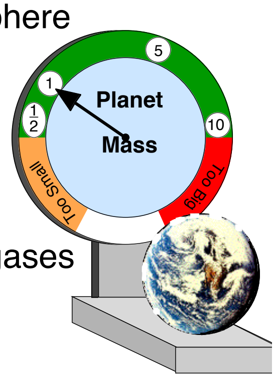
BUT - life exists in extreme environments on Earth
- liquid water a constraint for “normal” life only!

The Habitable Zone

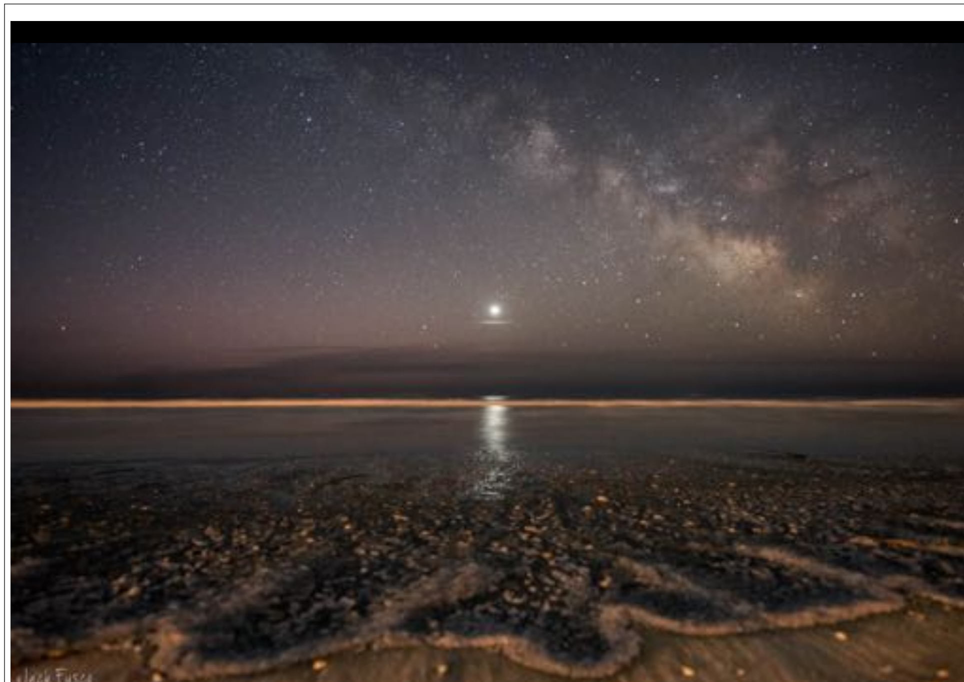


Planet Size and Habitability

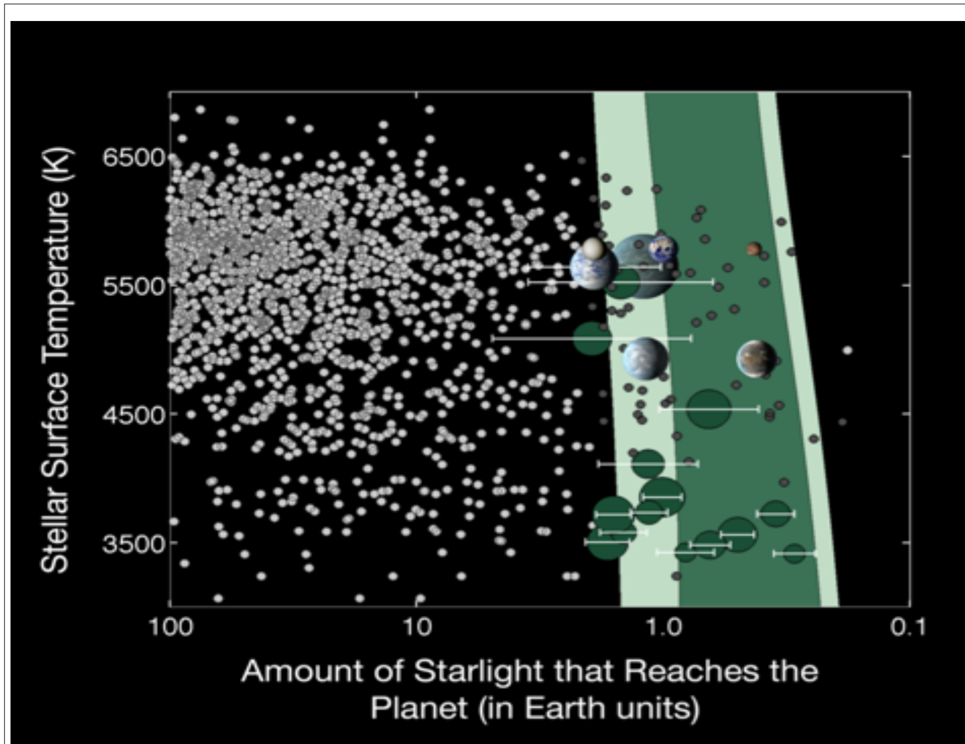
- **Too small** **(< 0.5 $M_\oplus$):**
  - Can’t hold onto a life sustaining atmosphere (Mercury, Mars)
  - no tectonics - no carbon regulation

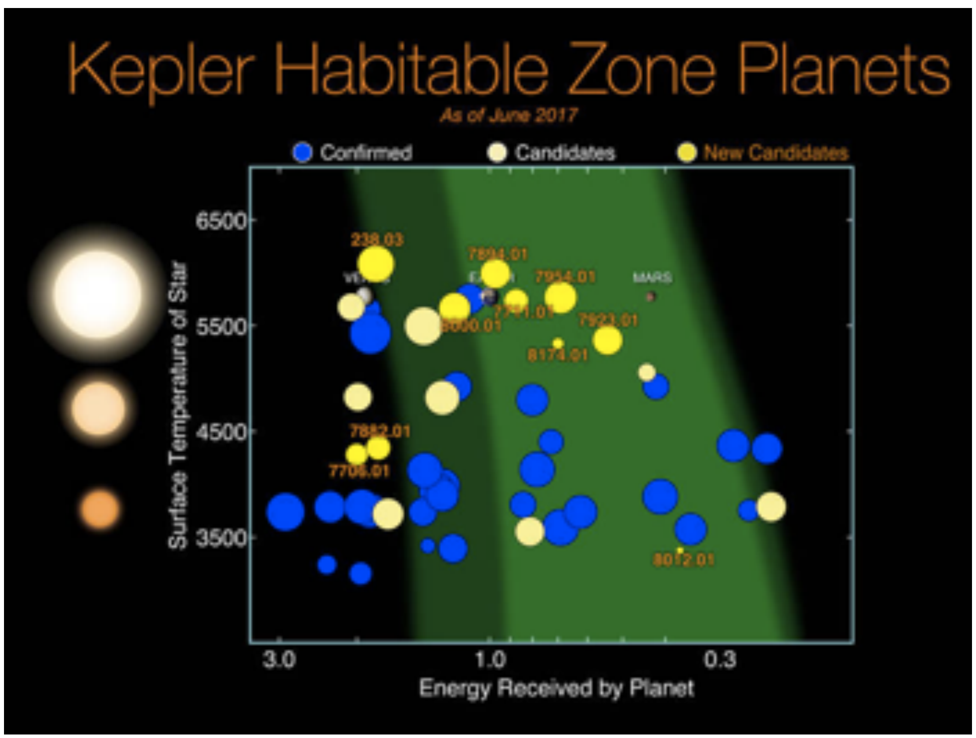


- **Too big** **(>10 $M_\oplus$):**
  - Can hold onto the very abundant light gases (H_2 and He)
  - turns into a giant (Jupiter, Saturn) or ice giant (Uranus, Neptune)



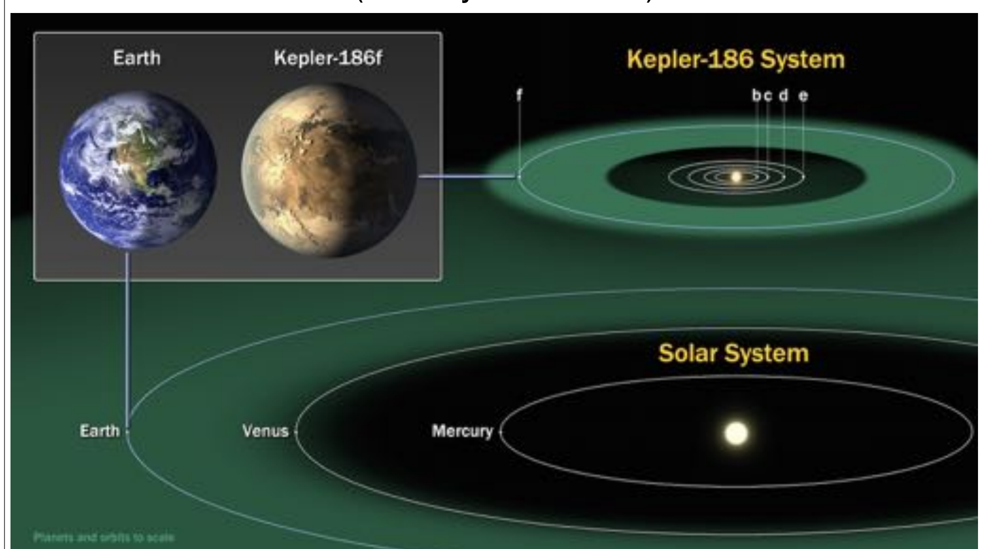
Venus, viewed from New Jersey: Astronomy Picture of the Day - 3/7/14



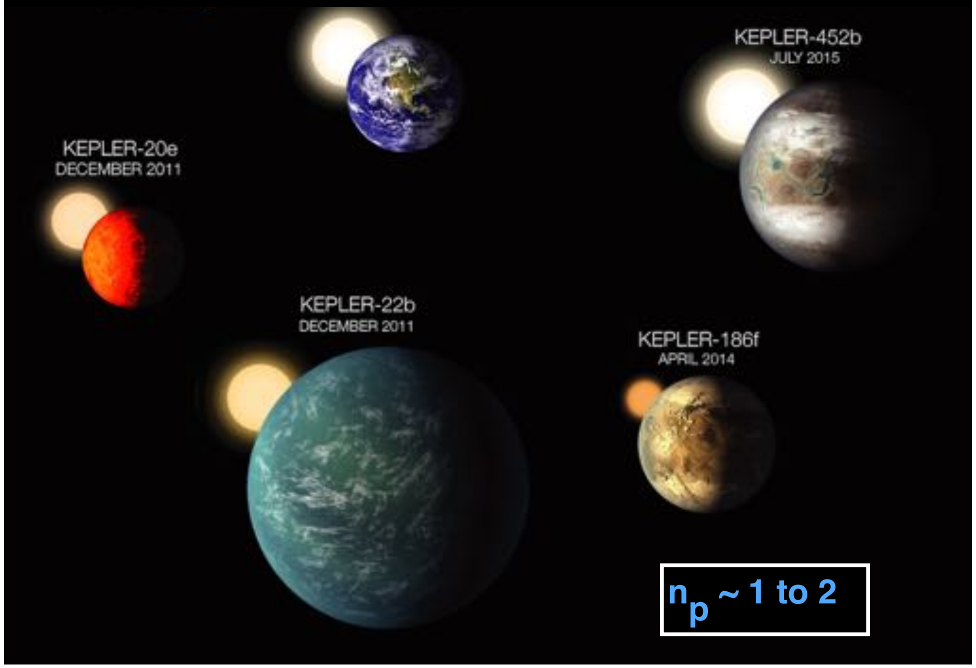


Kepler 186 system

(Barclay et al. 2014)

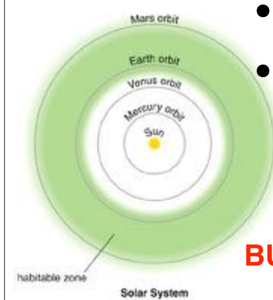


“Earths” from *Kepler*



n_p = habitable planets: the ‘Habitable Zone’

- water essential to life (as we know it)
- liquid water has to exist on (or in) the planet
- must be right distance from star
  - heat from star ~ maintain $0^oC < T < 100^oC$
  - too close - runaway greenhouse (Venus)
  - too far - CO_2 ice - no greenhouse (Mars)

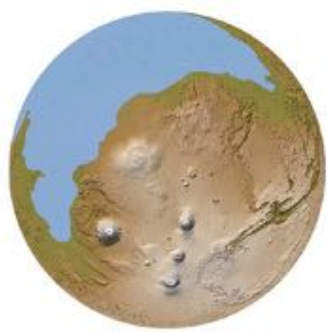


n_p ~ 1-2

BUT - life exists in extreme environments on Earth
- liquid water a constraint for “normal” life only!

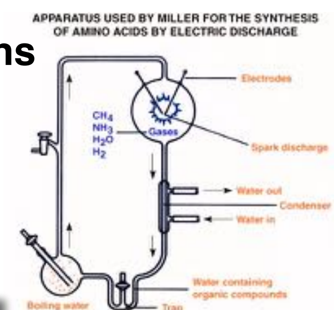
Biological Factors

- Given the proper ingredients
  - energy (starlight, lightning, geothermal...)
  - raw materials (carbon, hydrogen, nitrogen, oxygen)
  - time (1 billion years or so)
- **Will life develop? f_L**
- **Will intelligence develop? f_i**

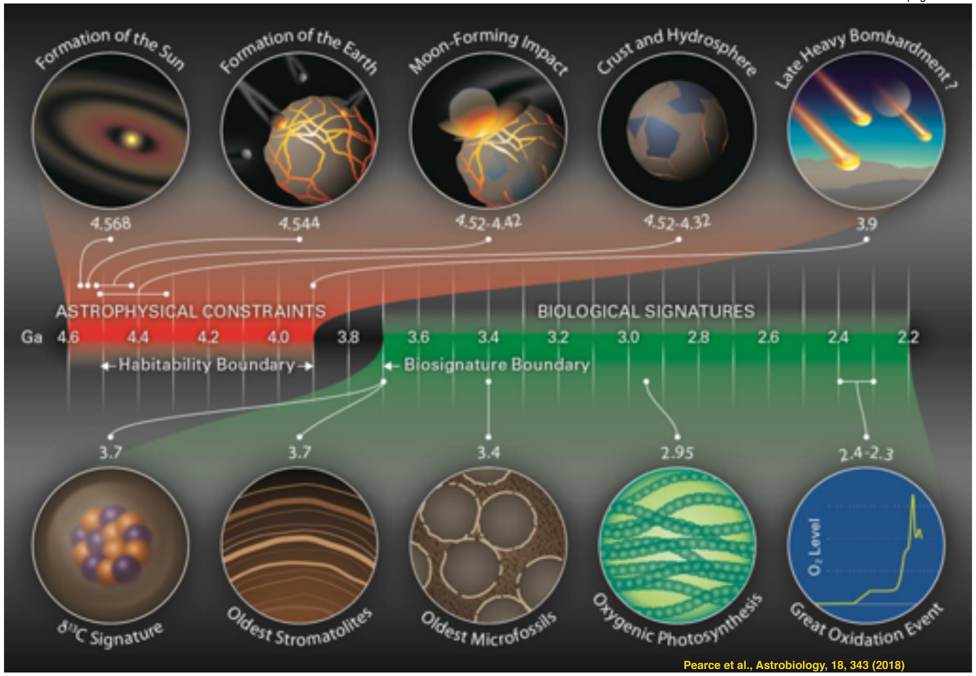


the Miller-Urey experiment (1953)

- **Simulate early Earth conditions**
  - water, ammonia, methane, CO_2
  - energy
  - time

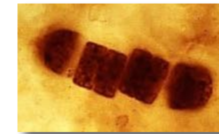


- **results:**
  - amino acids
  - organics
  - sugars



The Oldest Fossils

- Cyanobacteria date back to 3.5 Billion years ago
- appear very soon after end of era of heavy bombardment
- they remain one of the most common forms of bacteria today
- responsible for generation of oxygen in early atmosphere

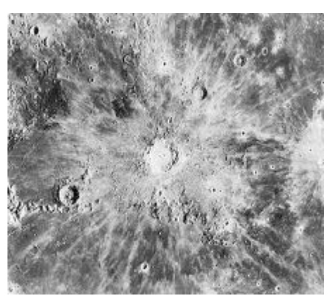

Palaeolyngbya (fossil)


Oscillatoria (modern)

f_L ~ 0.1 to 1 ?

recall: Cratering rates then and "now"

- **Lunar Results**
  - high rate in past (4 Gy ago)
  - now nearly steady
- **"recent" impacts**
  - Tycho: 100 My ago
  - Copernicus: 600 My ago



Late heavy bombardment

Pearce et al., Astrobiology, 18, 343 (2018)

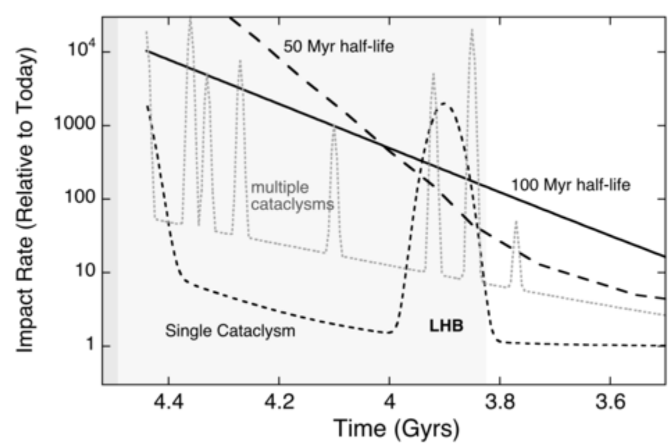
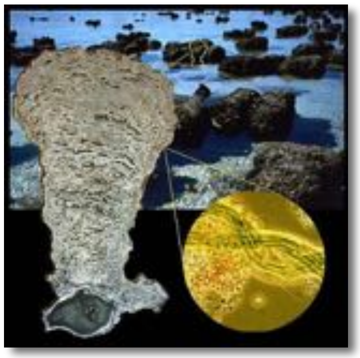


Figure 2. Four possible scenarios for the late heavy bombardment, calibrated to crater counts and surface ages at the Apollo landing sites. All scenarios except the 50 Myr half-life model are supported by the available data. Reprinted by permission from Springer Nature: Zahnle *et al.* (2007).

Life's Early Start on Earth

- earliest fossils in excess of 3.5 billion years old
- stromatolites - 1st 'macroscopic' form (bacteria colonies)



a view of life on Earth
ca. 2,000,000,000 B.C.E

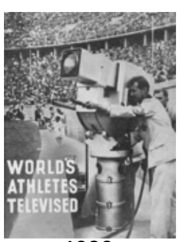
500 million years ago. . .

- the Cambrian 'explosion'
- increasing complexity and explosion of diversity
- ***leading to...***

$f_i \sim 0.5$? 1 ?

Sociological Factors

- $f_c = 1/2$?
  - at least 1, maybe 3 intelligent species on Earth
  - 1 with technology for remote communication
- L > 80 years
  - "Longevity" - how long are they detectable?
  - leakage of VHF/UHF signals into space
  - we have been detectable for almost 80 years



1936

1966

2019

Putting it all Together:

$$N \approx 8 \times 0.9 \times 1 \times 0.5 \times 0.5 \times 0.5 \times L$$

$$N \sim L$$

The number of other technical civilizations in our galaxy equals the number of years that they are able (and willing) communicate

Could be ~ 80 in our galaxy right now!